Martian Entry Simulation Using a Carbon Dioxide Test Gas in the Johnson Space Center Arc Jet Facility

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The Atmospheric Reentry Materials Structures Evaluation Facility (figure 1) —otherwise referred to as the Arc Jet Facility—is a high-enthalpy wind tunnel that is used for simulating the extreme environment a spacecraft experiences upon reentry into Earth's atmosphere. Ground testing within the Arc Jet Facility is critical throughout all phases of a spacecraft's lifecycle, beginning at basic material screening and characterization, through analysis validation and material qualification, and through mission support involving flight anomalies and material requalification.

The Arc Jet Facility accomplishes this demanding task via electrically heating air (referred to as the test gas) using a 13-megawatt direct current power supply and supersonically accelerating the resultant plasma over a test article. The power level and the test gas flow rate are then adjusted to obtain reentry-equivalent surface conditions such as temperature, pressure, and shear on the model surface. However, perhaps the most important aspect of the arc jet test is obtaining the reentry-relevant chemical environment. At hypersonic speeds, the energy imparted on the surrounding air can disassociate the diatomic molecules (O_2 and N_2) into their atomic components: oxygen (O) and nitrogen (N). Atomic oxygen is chemically reactive; a material that would normally survive high temperatures within an inert environment can catastrophically fail. In addition, it is possible for a material to promote the recombination of these chemical bonds, resulting in an exothermic reaction that can greatly increase the heating. This is referred to as catalytic heating. Thus, arc jets are critical to understanding and properly modeling the behavior of spacecraft thermal protection systems within this environment.

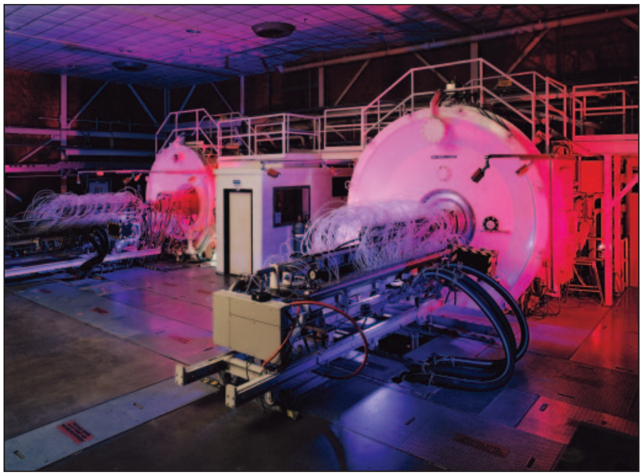

Fig. 1. Photo shows the two test positions at Johnson Space Center's Atmospheric Reentry Materials Structures Evaluation Facility.

The Arc Jet Facility simulates the Earth's atmosphere with individually controlled O_2 and N_2 test gas systems that deliver a 23:77 O_2:N_2 mass ratio within the arc heater. One major advantage of this configuration is the ability to dynamically adjust the O_2 ratio through the control system, from 0% up to 65%. The Mars Science Laboratory spacecraft is using a phenolic impregnated carbon ablator (PICA) as the heat shield. In 2008, engineers tested four PICA models in the Arc Jet Facility at varying O_2 ratios to better understand the impact of the atomic oxygen on the performance of this material (figure 2). All four PICA models were exposed to equivalent heating rates, impact pressures, and exposure durations, and a correlation of increased recession to increased oxygen content was evident. Since the Mars atmosphere can contain as much as 97% carbon dioxide (CO_2) by mass, a greater understanding of thermal protection system response to this radically different environment is required for accurate modeling and robust design to ensure mission success.

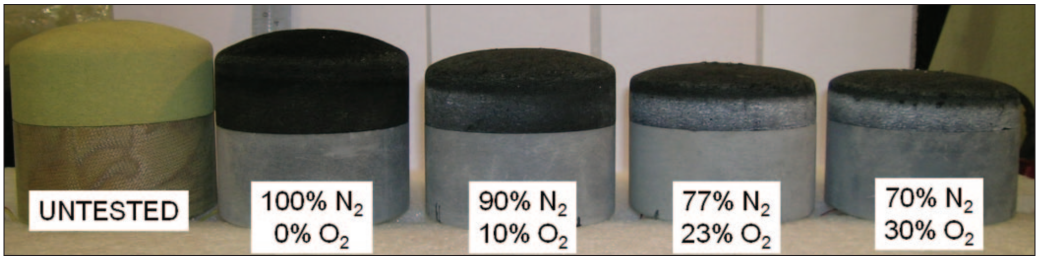

Fig. 2. Four-inch-diameter phenolic impregnated carbon ablator models following arc jet testing at varying levels of oxygen.

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In the summer of 2010, a concerted effort began in the Arc Jet Facility to add a CO_2 test gas capability to simulate a Mars atmosphere. The primary obstacle to overcome was in determining the amounts, if any, of carbon monoxide, cyanide, and hydrogen cyanide being produced, and whether the amounts posed a hazard to personnel and/or equipment. Since carbon monoxide can be an explosive hazard at certain pressures and concentrations, nitrogen was injected into the vacuum system as a dilutant. A residual gas analyzer was installed downstream of the heat exchanger in the vacuum system to sample the cooled exhaust gases. Also, after each test run with CO_2, an industrial hygienist analyzed surface sample wipes of the test chamber for the presence of cyanide. A secondary obstacle to overcome was in determining whether the presence of CO_2 within the arc heater was detrimental to its performance or to the lifespan of the electrodes.

Testing began at moderate CO_2:N_2 mass ratios to gain familiarity with the resultant safety data, and subsequent tests were performed with an increasing concentration of CO_2. In February 2011, engineers performed a test run on a PICA model with a 90:10 CO_2:N_2 mass ratio and a 2.60-megawatt power level (figure 3). The next test run, scheduled for the summer of 2011, is designed to achieve the final goal of a 97% CO_2 concentration. Throughout this effort, personnel found no detectable levels of cyanide. The production rate of carbon monoxide is now understood and can be managed safely. Also, the arc heater and electrodes performed remarkably well, with no failures. An efficient process has been developed to allow rapid transitions to Earth or Mars configurations.

In parallel with the data for safety, flow field calibration data were obtained in various forms. Stagnation heating rates and pressure readings were made with calorimeter probes. Laser-induced fluorescence was used for quantifying the velocity, temperature, and species concentration of the atomic oxygen.

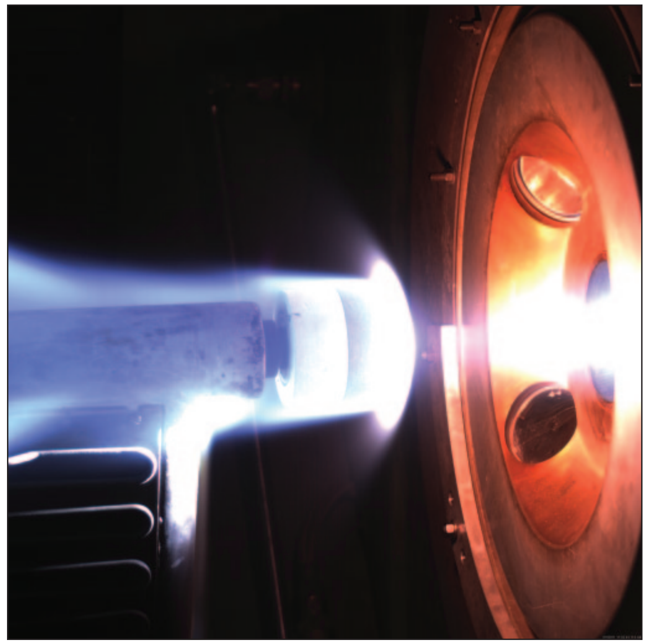

Fig. 3. *Four-inch-diameter phenolic impregnated carbon ablator model exposed to a 90% carbon dioxide environment in Johnson Space Center's Atmospheric Reentry Materials Structures Evaluation Facility.*

As a result of these efforts, engineers developed a unique capability for the agency and for the nation. No other facility worldwide has performed a successful arc jet test with 90% CO_2 at this power level and associated test gas flow rates. Future testing is planned to expand capability (up to 13-megawatt power level and higher gas flow rates), and to understand and accurately model the test environment via laser-induced fluorescence data, stagnation heat flux and pressure data, and probe sweeps of the flow field. This capability is a valuable, cost-effective tool for the thermal protection system community to screen, develop, and certify materials and systems for Mars and other CO_2-rich planetary entry environments.